Spatial Bayesian belief networks as a planning decision tool for mapping ecosystem services trade-offs on forested landscapes

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ABSTRACT

An integrated methodology, based on linking Bayesian belief networks (BBN) with GIS, is proposed for combining available evidence to help forest managers evaluate implications and trade-offs between forest production and conservation measures to preserve biodiversity in forested habitats. A Bayesian belief network is a probabilistic graphical model that represents variables and their dependencies through specifying probabilistic relationships. In spatially explicit decision problems where it is difficult to choose appropriate combinations of interventions, the proposed integration of a BBN with GIS helped to facilitate shared understanding of the human–landscape relationships, while fostering collective management that can be incorporated into landscape planning processes. Trades-offs become more and more relevant in these landscape contexts where the participation of many and varied stakeholder groups is indispensable. With these challenges in mind, our integrated approach incorporates GIS-based data with expert knowledge to consider two different land use interests – biodiversity value for conservation and timber production potential – with the focus on a complex mountain landscape in the French Alps. The spatial models produced provided different alternatives of suitable sites that can be used by policy makers in order to support conservation priorities while addressing management options. The approach provided a common reasoning language among different experts from different backgrounds while helped to identify spatially explicit conflictive areas.

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1. Introduction

Forests cover more than one third of the total land area of the European Union. They represent a key natural resource, which has been managed for decades to meet growing societal demands for diverse forest ecosystem goods and services. Forest ecosystem services (ES), the benefits that humankind obtains from forests both directly and indirectly, are important not only at regional levels but also at national and global scales (MA, 2005). For instance, flood regulation or soil erosion control services provided by forests have a direct impact on local populations, whereas carbon sequestration has a global influence. The incorporation of the ES concept into the framework of forest management leads to a more holistic perception of the role of forests, recognizing not only their economic value but also their cultural and ecological values, including their regulation capability. Yet, despite this improved understanding of the potential of forested landscapes and their land use systems to provide human well-being and socio-economic benefits, further conceptual and empirical work is needed to implement operational frameworks for integrating ES into management and decision-making (Carpenter et al., 2009). The concept of multifunctional landscapes, which assumes that landscapes have always fulfilled more than just a single aim such as producing basic ES like food, fibre, timber and fuel (Knickel and Renting, 2000; Mander et al., 2007; Gimona and van der Horst, 2007), has attracted the attention of scientists over the last few years (e.g. Brandt et al., 2000; Mander et al., 2007; Vejre et al., 2007). This approach has become of major importance in forest resource management and rural development (Dwyer, 2007; Bagstad et al., 2013) and is directly linked to the ES concept (Luque...
Within the framework of multifunctional landscapes, quantitative relationships between biodiversity, ecosystem functioning and ecosystem services are still poorly understood. In recent years, many publications have appeared on this topic (e.g. Elmqvist et al., 2010; Mace et al., 2012; Bastian, 2013), but many questions remain. There is also an on-going discussion as to whether biodiversity is (or should be understood as) an ecosystem service itself (e.g. Mace et al., 2012). Especially this latter question hints at the important point that the link between biodiversity and ecosystem services is not just a matter of biophysical relations, but also one related to value dimensions and different emphases of conservation strategies and human perceptions. It is still unclear under what circumstances an emphasis on ecosystem services in planning and decision making is (conceptually and practically) supportive of biodiversity conservation, or when the two aims may be conflicting. The complexity of ecosystem functioning still poses uncertainties about the role of individual species and other components of biodiversity in the supply of ecosystem services, specifically within coupled social-ecological systems. It becomes clear that one important challenge is to identify preferred trade-offs among several services (Schwenk et al., 2012) in evaluating forest management options (Carpenter et al., 2009; Chan et al., 2012; Gramfeld et al., 2013), and to see which trade-offs are relevant at different scales and contexts when integrating forest management into territorial planning.

Multi-criteria analyses can help forest owners and forest managers consider the best pathways to potential ‘win–win’ situations, or at least good compromises to enhance sustainable use of multiple ES. Accounting for trade-offs provides an alternative support to forestry planners who normally lack the funding, time and certainty to explore alternative management options. Thus, with growing interest in using ES for decision making, demand has grown for systematic methods and tools to quantify ecosystem service values (McCloskey et al., 2011; Pullin et al., 2004). Within this framework, the requirement for spatially explicit ecosystem valuation is based on the recognition that ES are context dependent in terms of their provision and their associated benefits and costs.

1.1. The importance of visual methods

When trying to facilitate the participation of stakeholders, especially (but not only) if they are not professional experts, a particularly efficient way to convey complex information is by the use of visual presentation. Visual information appears often easier to absorb than verbal information (think, for example, of the comparison between a lengthy table and a bar chart encoding the same information) Psychologists hypothesise, with some evidence (Evans, 2003; Sternberg and Leighton, 2004), that this is due to our evolutionary history, given that verbal skills have appeared much later than visual ones (e.g. Paivio, 2007; Mattson, 2014). Stanovich and West (2000) coined the term ‘System 1’ and ‘System 2’ to refer to the visual system that does ‘implicit’ and approximate processing, and the verbal system that does ‘explicit’ processing of information, often more accurate but also slower. Some authors even speculate that the ability to make and interpret maps might have played an important role in our evolutionary history (Landau and Lakusta, 2009). Others disciplines have already realised, empirically, the superior ability of the visual system to process information quickly: Tufte (1983) and Card et al. (1999) are seminal works, but the use of graphs and charts obviously predates these authors.

The upshot is that there are empirical and theoretical reasons why using visual methods are a valid and powerful way to communicate with others. A Bayesian belief network (BBN) is one of a family of graphical models that exploit the visual channel of perception to make information that would otherwise be difficult to grasp, especially for non-statisticians, more accessible. They do this by providing a pictorial representation – with a well understood corresponding mathematical description – of the conditional probabilistic dependency between variables. When co-constructing a system model, this enhances the ability of all participants to contribute. Within this context, BBNs are a powerful instrument to represent relationships (conditional dependence) and uncertainty, but they are unable to provide a direct, at a glance, representation of the spatial relationships between the variables that appear in them as nodes.

The spatial dimension of an environmental model is a key issue for local stakeholders, since they are more interested to know ‘where’ to implement planning than ‘why’. Usually, they have clear ideas of local and regional problems, but they need operational and spatial solutions (Fürst et al., 2014). For the perceptual reasons discussed above, a GIS providing maps and other diagrams is an obvious and natural tool to visualise such information efficiently, as the pattern of dependency between variables, the context in which local values are situated, the local variation and the long distance trends are relatively easily captured. An approach combining BBNs with geographical information systems (GIS) therefore has the benefit of conveying a large amount of information to stakeholders, of performing inference on a potentially very large amount of data, and of propagating uncertainty using a well-established Bayesian framework.

1.2. BBNs and their use in the environmental planning processes

A BBN is one type of directed acyclic graph, where nodes are used to hold information on the random variables (including parameters) in the model and their conditional interdependencies are represented by links or edges. The graph is directed, so there are one-way ‘parent’ to ‘child’ relationships shown by the links, and it is acyclic, meaning there can be no closed loops in the graph, i.e. no node can influence itself. Feedback loops are accommodated by introducing a time step, so a node can influence its corresponding node in the next time step. Child nodes depend only on their direct parent nodes, which means that nodes that are not directly connected are assumed to be independent of each other. This independence feature allows the joint probability distribution over all variables, which gives the outcome probabilities for the decision process, to be built up from the set of conditional probabilities that express the links between the parent and child nodes. Within a BBN, each node has a defined set of states within a conditional probability table (CPT), which defines for each child node state the probability of it occurring given all possible combinations of parent node states. Kjærulf and Madsen (2013) give the theory of Bayesian Networks and a detailed guide to their construction.

Because uncertainty is integral to Bayesian decision analysis, these models help decision makers to be aware of and include uncertainties regarding natural and social systems by organizing and presenting information in coherent and simple frameworks (Cowell et al., 1999; DEWA, 2010: Jensen, 2001; Pearl, 1988). The BBN structure is flexible in terms of enabling the direct integration of new variables or states into the graph (Haines-Young, 2011; Landuyt et al., 2013; Smith et al., 2007), so allowing exploration of new scenarios and alternative options which can be useful for decision and policy makers. BBNs can also be updated easily as new information becomes available. The Bayesian framework accommodates the impact of beliefs and preferences on the decision process, drawing together diverse sources of evidence into a single coherent description of a given problem, and providing a transparent model where the outcomes from conflicts of objectives and of evidence can be challenged (Smith, 2010).
BBNs have been used in many ecological and ES applications in recent years. Villa et al. (2014), present an integrated methodology that gives equal emphasis to their production, flow and use by society, Frayer et al. (2014) used BBNs to analyse household tree planting behavior in Yunnan, with influences ranging from the local (e.g. household income) to the national (e.g. forest policies). Van der Biest et al. (2014) built on a BBN which integrates the effects of biophysical and socio-economic processes with land-use planning policies, and this is linked to mapping the opportunities for increasing EES delivery and the optimal land use. Cello et al. (2014) uses spatially-explicit BBNs for 3 land use sectors representing the land use decisions, institutional arrangements and biophysical conditions within each sector, and these were calibrated by experts and local actors. A path-dependency analysis is used to give probabilities of land use states for future time points. Grêt-Regamey et al. (2013) used a BBN linked to a GIS to show how uncertainties affect both total value and spatial pattern of delivery of ES, an important consideration for long-term management of mountain forest ecosystems. Landuyt et al. (2013), who review the use of BBNs in many ES modelling approaches, include a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) to highlight advantages and disadvantages of the methodology, and conclude that they deserve further exploration and development.

In all, the ability of BBNs to integrate quantitative and qualitative information is a strong incentive for decision makers to access tools with all-inclusive information (Cain et al., 2003; Henriksen et al., 2007; McCann et al., 2006; Wang et al., 2009). Tools that facilitate the integration of individual perspectives and perceptions from different stakeholders into empirical models leading to a pragmatic and compact analysis, thus being of a great importance for land use and landscape planners (Haines-Young, 2009; McCloskey et al., 2011). Furthermore, BBNs can be used as a platform or focus of discussion between experts and/or stakeholders in order to analyse how a system works, to seek information on the appropriate probabilities, or to explore the usefulness of the decision process, see, for example, Haines-Young (2011).

Policy and decision makers require spatial tools that help identify potential areas for ES delivery at landscape scales (Kienast et al., 2009). As aforementioned, there are several examples of ES mapping studies at different scales, going from global (Haines-Young et al., 2012; Maes et al., 2012; Naidoo et al., 2008; Turner et al., 2007), to national (Egoh et al., 2009; Schneiders et al., 2012) and local (Bryan et al., 2011; Burkhard et al., 2012; Chan et al., 2006; Fagerholm et al., 2012). However, a significant amount of research has focused on analysing the linkage between certain ecosystems and the supply of particular services, instead of performing holistic and integrated assessments. In this regard, assessing landscapes as areas which consist of bundles of services and trade-offs fosters a more divergent land management strategy with potential benefits for multiple stakeholders. Different methods have been used to identify and analyse ES bundles and trade-offs, from basic mapping of ES associated with particular land uses (e.g. Nelson et al., 2009; García-Nieto et al., 2013) to indicators for specific ES (e.g. De Groot et al., 2010), or by using Service Providing Units as the basis of the analysis (e.g. García-Nieto et al., 2013).

Our work is aimed at meeting the high demand by forest planners and land use policy makers regarding ES and biodiversity assessment tools (Seppelt et al., 2012), focusing on a spatially explicit biophysical assessment of ecosystems. The analysis of trade-offs and synergies among ES and biodiversity should provide insights for sound environmental governance at multiple scales, with the aim of enhancing sustainable practices for managing forests while still supporting biodiversity conservation and related ES. We test the approach on a case study in the French Alps, where the various bundles of ES represent the different conditions across the complex mountain landscapes. This study develops and implements a spatially explicit analysis based on a BBN that integrates GIS and expert knowledge regarding two different land use interests – biodiversity conservation and forest production potential. The case study at the ‘Quatre Montagne’ region located in the North of the Vercors’ Regional Natural Park (VRNP) was selected to develop the models.

Fig. 1. Study area location in the Alpine Mountain Range and the site of ‘Quatre Montagnes’ at the north of Vercors Regional Park (VRNP), French Alps. (Adapted from Parmentier (2013)).
2. Material and methods

2.1. Test area description

2.1.1. Location

The VRNP is a 206,000 ha area located at the border between the Northern and Southern French Alps (Fig. 1). 139,000 hectares of VRNP are dominated by forest land, with altitudes varying from 180 m to 2453 m. The main tree species are Silver Fir (Abies alba), Norway Spruce (Picea abies) and European Beech (Fagus sylvatica). Approximately half of these forests are Public (State and Municipality forests – dark grey in the map) and the rest is in the hands of private stakeholders (light grey). The particular case study selected for this research focuses on 25,000 ha (12% of the total area) located at the North of VRNP, in an area known as ‘Quatre Montagnes’. Fig. 1 shows the Quatre Montagnes region within the Regional Natural Park in the French Alps, (in dark green, public forests). The area is encompassed by seven communes that constitute its region.

The main processes influencing changes and shifting land use in VRNP are afforestation, artificialisation (i.e. increase in urban sprawl, mainly in valleys), and, to a lesser extent, deforestation (Parmentier et al., 2013). In particular, afforestation (Barbero, 2000; Mather, 2000; McCormack and O’Leary, 2000; Pryor, 2000; Tyrvainen and Tahvanainen, 2000) and artificialisation (Djokic, 2009; Pointereau and Coulon, 2009) have been widely studied in the scientific literature, mainly related to changes in management strategies to achieve different levels of land use and conservation. These particular anthropogenic interventions have taken place in this region for centuries, and are similar to changes in other forested areas around Europe. This has led, together with other factors such as varying climate and the characteristic heterogeneous topography of the region, to complex landscape mosaics of natural and semi-natural habitats at Quatre Montagnes (Parmentier et al., 2013). Fig. 2 shows the land use/land cover (LULC) at Quatre Montagnes, VRNP, France. Note that open-lands (yellow color), urban areas (black color) and water bodies (blue color) have not been considered in our research study, as the focus is on forested areas.

The LULC shown in Fig. 2 is the product of the cultural, historical and biophysical interactions that shaped the mountain landscape we perceive nowadays. The complexity of these

Fig. 2. Land use/land cover map at ‘Quatre Montagnes’ Vercors, France. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
Table 1 Description of the spatially explicit biophysical variables used on the Bayesian network as input nodes to assess the suitability of forest production and biodiversity interests, for the ‘Quatre Montagnes’ study area (see Redon (2012), Parmentier (2013)).

<table>
<thead>
<tr>
<th>Variable/node</th>
<th>Description</th>
<th>Categories</th>
<th>GIS layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest age</td>
<td>Forested area, classified by forest age structures. We assume ancient forests to be the most valuable from conservation purposes (Duponse et al. 2002), followed by adult and recent categories.</td>
<td>Ancient, Adult, Recent, NA</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>PSB indexc</td>
<td>Forest heterogeneity, obtained through spatially explicit multi-scale analysis. We assume areas with high PSB to be the most valuable from the perspective of conservation (Redon, 2012).</td>
<td>High, Moderate, Low, NA</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>Habitats of community interest</td>
<td>Areas of community interest based on European Habitats Directive.</td>
<td>Very high, high, moderate</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>ZNIEFF Type I and II</td>
<td>Areas covered by both ZNIEFF I and II. ZNIEFF: Natural zone of ecological interest, in terms of fauna and flora. The designation of a ZNIEFF is based primarily on the presence of species or groups of species with strong heritage interest. Type I: areas with at least one species or habitat in critical status. Type II: areas with an important functional role within the ecosystem. We assume areas inside ZNIEFF to be valuable from a biodiversity conservation perspective.</td>
<td></td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>Sensitive Natural Areas (SNA)</td>
<td>Protected forested area with unique or highly-valued landscapes, wildlife and historical nature.</td>
<td>Current Conservation Site, Close (0–100 m), moderate (100–250 m), far (beyond 250 m)</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>Biological Integral Reserve (BIR)</td>
<td>Protected forested area with human intervention limited</td>
<td>Current Conservation Site, Close (0–100 m),</td>
<td>![GIS layer image]</td>
</tr>
</tbody>
</table>

Table 1 (continued)

<table>
<thead>
<tr>
<th>Variable/node</th>
<th>Description</th>
<th>Categories</th>
<th>GIS layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natura 2000</td>
<td>EU wide network of nature protection areas under the 1992 Habitats Directive. Zone of valuable and threatened species and habitats.</td>
<td>Current Conservation Site, Close (0–100 m), Moderate (100–250 m), Far (beyond 250 m)</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>Productivity Potential</td>
<td>Forested area with potential to produce timber, based on soil, climate, accessibility and present forest structure as indicators. (adapted from Dreyfus, 2011; Dreyfus, 2013), (produced by Parmentier, 2013)</td>
<td>Very High, High, Moderate, Low, Very Low</td>
<td>![GIS layer image]</td>
</tr>
<tr>
<td>Forest Ownership</td>
<td>Area distribution for public and private forest ownership. We assume public forests to have higher probabilities to enhance conservation supporting management strategies.</td>
<td>Public, Private</td>
<td>![GIS layer image]</td>
</tr>
</tbody>
</table>

* BBN categories are the same as the classes from the original GIS layers.  
* Not available data. Refers to those areas (i.e. pixels) with no values assigned in the original GIS layers. These areas were given equal probabilities in the CPTs.  
* Potential species biodiversity index (Redon, 2012).  
* Natural zones with ecological, floral and faunal interest.

processes make this area an appropriate exemplar in the Alps region for conducting forest land suitability assessments, allowing a focus on critical mechanisms such as forest productivity interests and biodiversity conservation goals. The identification of factors associated with these trade-offs are crucial for the understanding of interactions and synergies between ES and biodiversity through a multidimensional approach as presented here.

2.2. Data

The data used to build the BBN are based on GIS layers from different biophysical and ecological components, in addition to using outcomes from a participatory process with different stakeholders and expert opinion.

2.2.1. GIS Layers

Table 1 shows the GIS layers retained for the study; namely forest age, potential species biodiversity index (PSB index, Redon...
(2012)), habitats of community interest, natural zones with ecological, floral and faunal interest (ZNIEFF), sensitive natural areas (SNA), biological integral reserves (BIR). Natura 2000 sites, productivity potential and forest ownership. All are based on biophysical indicators and were developed in the Spatial Analysis and Landscape Ecology lab at Grenoble, France (see Redon (2012), Parmentier (2013) for more details).

2.2.2. Participatory process

We included outcomes from a participatory process performed between 2011 and 2013 at VRNP. Different stakeholders were brought together with the objective of understanding their particular short and long-term goals regarding the actual land use and their vision for the future, not only for forest management but also for an integrative approach balancing conflicting interests in relation to territorial planning at VRNP in general and Quatre Montagnes in particular. We used a type of participatory process known as the ‘Territory Game’ (Lardon et al., 2012; Lardon, 2013) which advocated a collaborative learning system to create models of territorial governance (Angeon and Lardon, 2008) using a forward-looking, problem-solving process supported by spatial models and carried out as an interaction between participants and scientists (Lardon and Piveteau, 2005). The spatially-explicit material produced for the workshops showed land cover changes for the region from 1840 until 2000 (see Parmentier (2013), Parmentier et al. (2013)). This particular section of the workshop was set up to collect information on the future needs and wishes. In parallel, we developed scenarios for 2030 and 2050 horizons in order to address the future management issues raised by the various stakeholders during the participatory process. This process developed hypotheses based on analysing trade-offs between land management needs and land use. Finally, the methodological challenge was to implement models that were not designed to reproduce exactly the land use of the past but to integrate the processes and landscape drivers of change responding to the local dynamics, whether natural or anthropogenic. Other biophysical maps for different indicators were also provided to workshop participants to provide the basis for building up the final scenarios looking towards 2030 and 2050 (Parmentier et al., 2013).

The workshops were up to a half hour duration with the aim of ensuring the mixing of different local actors (e.g. farmers, forestry representatives and others) in different groups and of enhancing collaboration. This process allowed actors not only to express their perspectives and interests to the rest of the community, but also to solve local problems in a holistic and shared manner (Lavigne-Delville et al., 2000). The stakeholders contributed new information and insights on their perspective of landscape functioning and related ecosystem services and how the analysis of alternative futures could be built, thus assisting in the critical task of envisioning future changes. The main conclusion from the participatory process was a need to increase timber production in both accessed and non-accessed areas, along with a will to maintain the high degree of biodiversity present in the region that attracts tourism and helps support traditional practices.

2.3. BBN building process

Fig. 3 shows the BBN building process, which followed a logical framework adapted from Marcot et al. (2006) and the Australian Department of the Environment, Water, Heritage and the Arts (DEWHA, 2010).

Nodes and Conditional Probability Tables

Tables 1 and 2 present and describe the different variables (i.e. nodes) used to construct the BBN. They are divided in two groups: nodes based on GIS layers (Table 1), and those representing the outcomes from the participatory process (Table 2).

Prior to using the spatial BBN software to produce the spatially explicit outputs, the GeNiE® BBN builder tool was used to develop the BBN framework (Landuyt et al., 2014). The causal probabilistic network structure is shown in Fig. 4, which integrates and links the nodes from Tables 1 and 2. Both input and intermediate nodes end up in what we call the ‘conservation’ and ‘production suitability’ nodes. These are the parent nodes of the final suitability node, which is the variable from which the mapped outputs were obtained. As a baseline, we used the land cover map for the Quatre Montagnes region adapted from Corine Land Cover and updated based on remote sensing data (Redon, 2012).

The probabilities from the conditional probability tables (CPTs) in each of the nodes, shown in Fig. 4, are a product of different processes. The input node CPTs reproduce the data in the GIS layers, thus no further interpretation was needed for their completion. The CPTs for the intermediate nodes were based on information from the participatory process performed with local stakeholders (Angeon and Lardon, 2008; Lardon et al., 2012; Lardon, 2013). Thus their goals and interests were integrated as probabilities that link the states in these nodes. Finally, the CPTs from the conservation and production suitability nodes, together with the final suitability node, were completed using expert opinion. Fig. 5 shows the CPTs of the suitability nodes which were completed by the experts (Lardon, 2013). The different actors and experts came from 20 different organisations and institutions, public and private, and were organised into three different groups. They first provided a diagnostic of the situation and then, at a second workshop, provided direct inputs to the probabilities and scenarios presented for incorporation into the model (for more details see Lardon et al. (2012), Lardon (2013), Parmentier (2013)).
In order to obtain spatial explicit outputs from the BBN, a tool, bayesGIS (Lasfargas et al., in preparation), was developed. This tool enabled us to integrate the BBN constructed with GeNIe (Fig. 4) and the GIS layers presented in Table 1. The tool uses a combination of routines implemented in R language (R Core Team, 2014). The tool can use spatially explicit input data as raster grids (see Tables 1 and 2) as well as non-spatial information, such as expert opinion. The tool uses the full spatial capability of R via the
Fig. 5. CPTs of the suitability nodes completed from opinion-based analysis for each interaction between states. For instance, those pixels with high conservation suitability and low conservation suitability states were considered high suitable for conservation.

Fig. 6. Final suitability maps considering trade-offs target areas with high potential for intensification of forest management practices (in brown, left side) as opposed to areas with conservation suitability potential (in green, right side). The final map in red represents areas showing conflicts (darkest red) in terms of trade-offs to balance interests of potential forest productions and biodiversity conservation targets. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
following libraries: raster for spatial data preparation, computation and visualisation (Hijmans and van Etten, 2013) and rgdal for data management (Keitt et al., 2009). Thus, the tool executes the BBN inference calculations for each of the raster grid cells of the input data. The libraries used for the BBN inference were bnlearn (Nagarajan et al., 2013, Scutari, 2010) and gRain (Hojsgaard, 2012). The outputs are raster maps where the pixel values correspond to the probabilities of a certain state for the target variable, i.e. the node for which the inference is calculated.

When a large amount of data is available, this tool can learn the network structure using constraint-based algorithms (Scutari, 2010). However, experts can also specify the causal structure using their prior knowledge of the system. Hence, the tool was used to perform inference on the combination of variables co-occurring in each grid cell, and to produce the corresponding probabilistic maps. These outputs were then submitted to further expert opinion that allowed for adjustment of the corresponding probabilities to match causal structures, and a combination of local and expert knowledge was used to produce the final maps. Overall, expert opinion proved to be useful in modifying and adjusting the spatial outputs; this was possible because the spatial outputs allowed an interactive reasoning to integrate sustainable territorial management initiatives.

3. Modelling results

The BBN, developed using GeNle, provided a useful framework to represent relationships between variables, even if the relationships involved a certain degree of uncertainty. The framework proved useful to better understand the logical context and evaluate potential conflicts. In particular, within the context of this case study used as exemplar, it was very relevant in estimating trade-offs between the needs to increase timber production while at the same time assessing suitability for biodiversity conservation. Fig. 6 shows the spatial explicit outputs obtained through the spatial BBN tool (bayesGIS). We produced one map of probabilities for each of the states in the final Suitability node. Each of the maps represents the probability from low to very high, producing a zoning of suitable areas in the map. The geographically explicit models show suitable areas with high biodiversity potential and areas with high potential for timber production highlighting trade-off candidate areas to target territorial planning decisions. The classification method to define the classes in each map was performed through ArcGIS, based on a ‘jenks natural breaks optimization’ (Jenks, 1967). This method reduced the variance within classes and maximized the variance between classes (McMaster, 1997) identifying groups of values, so that the values contained in each class are as similar to each other as possible, while the mean of each class differed from the rest of classes as much as possible.

3.1. High conservation suitability model

Fig. 6, to the right, shows the spatial distribution of suitable areas considered of high biodiversity value within the study area. Values range from low suitability for biodiversity (light green) to highly suitable sites showing high biodiversity value (dark green color). Based on the Jenks natural breaks optimization method, five classes of values were produced: very low (0–0.2), low (0.2–0.32), moderate (0.32–0.42), high (0.42–0.56), very high (> 0.56).

In all, very high and highly suitable areas for conservation cover only 20% of the total forest land area at Quatre Montagnes (Fig. 6). There are no noteworthy trends within the area, although north and south-east regions possess several high and very high suitable areas (>0.4). Among all the indicators used to build up the ‘Total Suitability’ models, protected areas were considered by experts and local stakeholders to be the most influential and important in terms of ecological value. Hence, buffers were created from each protected area to analyse the influence of conservation sites in the landscape (De Fries et al., 2010; Palomo et al., 2012).

Justification of the buffer distances is based on expert opinion and previous work (Redon, 2012) performed in the area to analyse the effect of the protection status. The further the areas from the protected areas the lesser the value, with areas close to each protected area (i.e. 0–100 m) given a higher value. Thus the conservation suitability values in the final map decreased from inside the protected area towards outside. Modelling buffers distances from inside to outside areas with special protected status helped to integrate differential ecological values according to protecting schemes and strategies.

3.2. High production suitability model

Fig. 6, on the left, shows the spatial distribution of high suitable areas for timber production. Like the conservation suitability output, the probabilities are shown in a pixel by pixel basis through a red color scale, ranging from values with areas of low probability to be highly productive (clear brown–red color), to values of high probability in terms of productivity potential (dark brown–red color) (Table 1). The final classification method for the probabilities was based on Jenks natural breaks optimization to be considered within the spatial BBN calculations, the same used for biodiversity suitability classes in order to keep consistency for the analysis. High and very high suitable areas for timber production cover 15% of the entire forested land area at Quatre Montagnes. There exists a north–south trend from higher potential forest towards lower potential, based on the ‘Productivity Potential’ variable (see Table 1, adapted from Dreyfus (2011, 2013)). This is mainly due to physical drivers characteristics for soils and climatic gradients that exist in the area (Redon, 2012).

3.3. Trade-offs between conservation targets and timber production potential

In Fig. 6, the center map shows a conflicting situation where areas having high biodiversity potential and also high timber production potential were highlighted (darker red color). The probabilities are shown in a pixel by pixel basis through a red color scale, ranging from values with low probability for trade-offs (light red) to areas for trade-offs (dark red). As in the previous models, the final value distribution was obtained using the same method and was based on five sub-groups: very low (0–0.31), low (0.31–0.41), moderate (0.41–0.45), high (0.45–0.55), very high (0.55–0.85).

There is a trend, in the northern section of the Quatre Montagnes region showing higher values, gradually decreasing as we move towards the south. This is due to important ecological zones with particular protection status like the biological integral reserve, Natura 2000 sites, sensitive natural areas or ancient forests that increase the conservation potential in the northern regions of the study area. Likewise, we found production suitability values ranging from moderate to very high in the same areas. As a result, there is a high potential for trade-off zones between protection and forests productivity potential in these areas. We found 85% to be the maximum probability where the two variables analysed collide.

4. Main findings, policy implications and options for further research

4.1. Main case-study findings and lessons learned

In this region different conflicting issues needed to be investigated, looking at trade-offs of different objectives in order to
help targeting conservation priorities and production management options. Bayesian Belief Networks provided a common reasoning language between people/experts from different backgrounds to find a common ground and redefine interests and needs. Still in order to get spatial information to support planning, BBN alone was not enough. The implementation of GIS along BBN helped to understand spatial trends while identifying target areas for planning. This example, provided a good case showing the advantages for ES mapping to provide information to decision makers, in this case to target areas where certain management practices can be carried out without influencing other activities (McCloskey et al., 2011).

The primary finding is the identification of areas with different conservation and timber production levels, and areas with a potential for trade-offs. There is also areas where forest management can be intensify in private land where high productivity potential was shown in particular towards the east and south of the region. There are also sectors where forest is slightly exploited because of accessibility issues; therefore improving access will open areas of productivity potential. While we perceived an improvement in the consideration of biodiversity related interests to be included into forest management practices; there is a need and interest to develop multifunctional activities in the region. At the same time other conflicts were identified linked to pressures coming from tourism related activities in the region and urban sprawl that needs to be controlled in the valleys.

In the study area, the north presents more conflicting zones but also areas with higher potential in terms of habitat quality and capacity for maintain or increase conservation. The spatial buffers set up from protected areas of special status, provided good indicators of the impact of conservation outside specific protection status. In that sense, the results obtained could be used for coordinating opposing interests like regional development and the quality of life and the preservation of biodiversity in the Alps region. The importance of protected areas for regional development cannot be assessed on the basis of value-added alone; they are of multifunctional value, and that value cannot always be precisely measured. Within this vein, the spatial BBN approach performed allowing the integration of different variables (Tables 1 and 2) in order for the spatial modelling to advocate for different landscape functions accounting for ES trade-offs and bundles. The approach could certainly support answers raised by the stakeholders in the Alpine region such as: under what conditions can major protected areas contribute to both regional value-added and the preservation of biodiversity? Or how can the preservation of biological diversity be a priority of concern? The approach fostered divergent land management strategies providing potential benefits for multiple stakeholders.

On a broader context, building up BBN by integrating stakeholder-driven processes with biophysical data can also be considered a starting point for combining models from different scientific areas, such as agriculture, urban development or health (see for example Sandifer et al. (2015), Quinn et al. (2013a, 2013b)). This combination of models from different disciplines could help in developing large interdisciplinary cross-cutting networks, which could be used successfully to support policy makers at different governance levels (e.g. Brunckhorst, 2000; Rouget et al., 2006a, 2006b). Likewise, they could help in the analyses of marginal changes in outputs and values associated with different policy options, and examining the trade-offs to be considered when exploring alternative scenarios for integrative forest landscape evaluations (Haines-Young, 2011).

4.2. Outlook

All in all, the method proved useful in unifying knowledge and putting it in a format suitable for reasoned argument. It provided a general framework to open a public dialogue reconciling biodiversity conservation with the increased demands and pressures on natural resources. In this sense, the participatory process helped to strengthen the sense of belonging not only to the territory itself, but also to the different institutions to which each actor belongs (Angeon and Lardon, 2008).

We are facing nowadays a real challenge, translated into a dual requirement for optimized production while preserving environmental quality and well-being. Increasing pressures to produce more is translated into forests management that includes different services rendered by forest ecosystems. Another aspect that needs to be considered is the vulnerability of the system to an intensification of wood stands. Faced with such challenges, a modelling tool as the one presented here, offers local players indicators that help to define the potential for increased wood production while preserving biodiversity in forests.

As climate changes, societal demands for goods and services from forests are also changing. The recent decision of European government leaders to increase the share of renewable energy in Europe to 20% by 2020 (targets of the Europe 2020 strategy for smart, sustainable and inclusive growth), is expected to result in a much greater demand for forest biomass for bio-energy generation. This higher demand will intensify the competition for resources between forest industry, the energy sector, and nature conservation/other protective functions and services (including biodiversity, protection from natural hazards, landscape aesthetics, recreation and tourism and climate regulation). Then we need tools to inform on what level of spatial scale adaptation measures can be effective: can they just do it by managing the land within their jurisdiction, or are they dependent on changes at broader scales and do they need to collaborate with other land managers around? Bayesian belief networks (BBN) as showed here, may be considered as a good modelling approach capable of representing decision making, behavior, adaptation, and other complex dynamics.

Further, the framework used provided baselines for resolving conservation versus development conflicts, highlighting that more collaborative land-use and landscape planning is needed (Redpath et al., 2013). Advocating an integrative forest land management through considering multiple interests from stakeholders is essential in land-use and landscape planning (Cowling et al., 2008; Haines-Young, 2009; Sieber, 2006). The experience of this case study as an exemplar could help addressing potential ES trade-offs in broader contexts, while gaining evidence for more holistic and multifunctional perspectives that can be enhanced through participatory processes (Haines-Young et al., 2006; Potschin and Haines-Young, 2003). Yet, local and regional management of ES is known to better meet the principles of land use and landscape sustainable development (Durán and Thoenig, 1996). Hence, as presented here participatory processes that enhance discussions and open dialogue among different actors provide channels for successful community-based planning background (Song and M’going, 2001; Fürst et al., 2014).

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